Argonne National Laboratory

Marianne M. Mintz

Hydrogen, Fuel Cells, and Infrastructure Technologies Program

Systems Analysis Workshop

July 28-29, 2004

Washington, D.C.

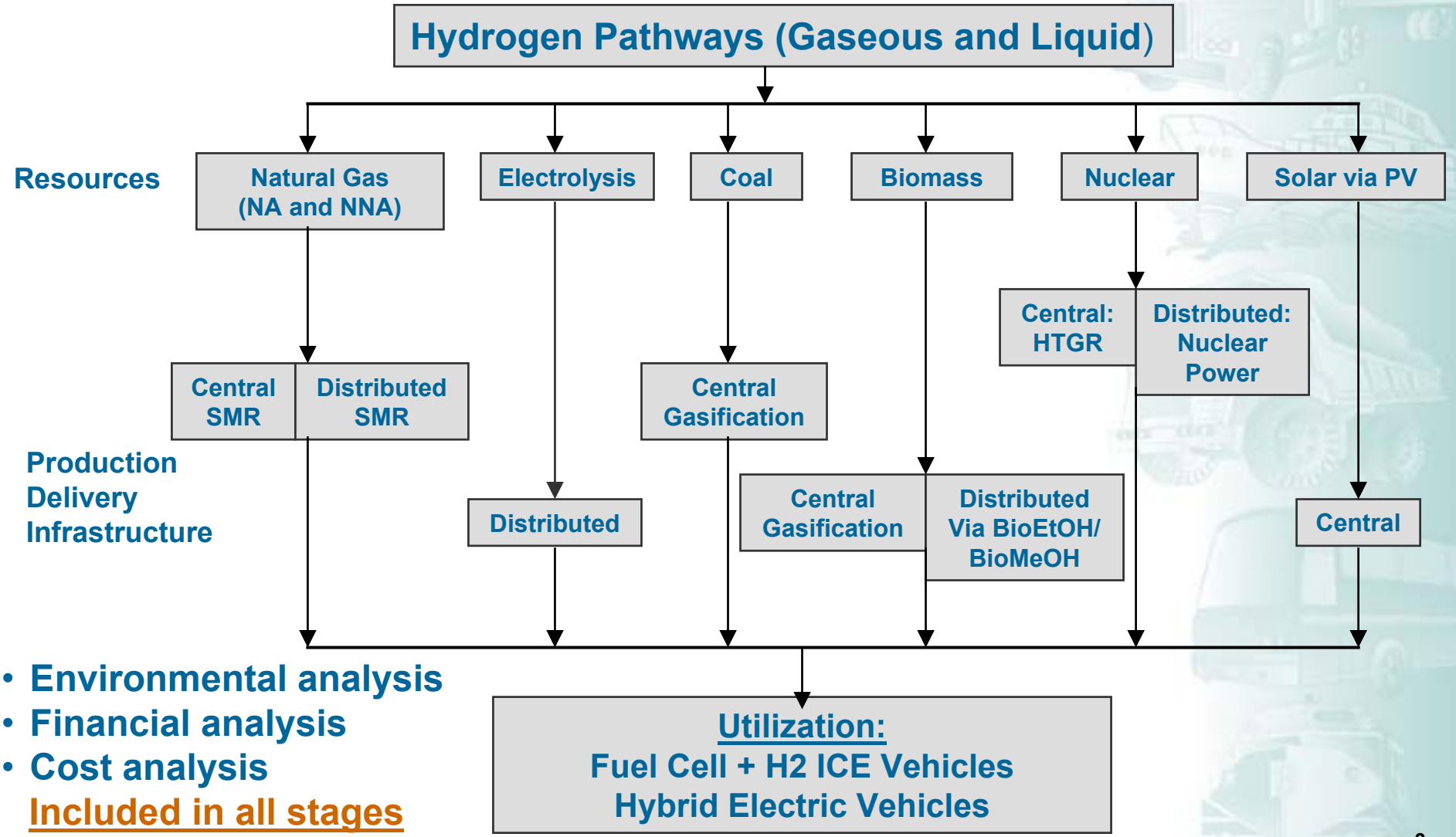
Center for Transportation Research
Argonne National Laboratory

A U.S. Department of Energy Laboratory
Operated by The University of Chicago

ANL's Charter

- **Systems analysis in Energy Systems (CTR), Decision and Information Sciences**
- **History of working in partnership with industry**
- **Analytical work has spanned the range of:**
  - ✓ Energy Supply – globally and by region
  - ✓ Demand for transportation fuels – globally and region
  - ✓ Assessment of vehicle technologies and fuels
  - ✓ Economic analysis and interaction between energy prices and macro activity
  - ✓ Life-cycle analyses of energy use and environmental impacts associated with transportation technologies and fuels
  - ✓ Evaluate policies to accelerate transitions to new fuels and vehicles
- **Funding sources**
  - ✓ Office of Hydrogen, Fuel Cells, and Infrastructure
  - ✓ Office of FreedomCAR and Vehicle Technologies
  - ✓ Office of Budget and Policy Analysis/EERE
  - ✓ Office of Fossil Energy
  - ✓ Office of Nuclear Energy, Science, and Technology
  - ✓ Office of Science
  - ✓ DHS, DOD, other military
  - ✓ Other government agencies (EPA, State of Illinois)
  - ✓ Private sector (GM/GAPC, GM/EMD, ADM, etc.)

ANL Takes a Comprehensive Approach to H2 Analysis



- Environmental analysis
- Financial analysis
- Cost analysis

Included in all stages

ANL's Analytical Efforts Span the Range Interest

- **Energy Resources:** from petroleum, fossil, nuclear, renewable sources – globally and by region
- **Technology Feasibility and Cost Analysis:** fuel cell and vehicle efficiency and performance modeling, vehicle cost modeling, resource feedstock availability and cost, hydrogen distribution options
- **Environmental Analysis:** Well-to-Wheels Greenhouse Gas and criteria emissions, local and regional impacts of alternatively–fueled vehicles
- **Delivery Analysis:** GIS analysis, infrastructure requirements and options
- **Infrastructure Development and Financial Analysis:** industry-defined agent-based complex adaptive systems
- **Energy Market Analysis:** hydrogen demand estimation, market penetration under different technical and economic assumptions, fleet turn over, agent-based predictive models of market behavior

ANL's Skill Set - People

- **Center for Transportation Research:**
  - ✓ Life Cycle Analyses (GREET) – Dr. Michael Wang and 4 staff
  - ✓ Infrastructure, Cost, and Financing – Marianne Mintz and 6 staff
  - ✓ Vehicle Modeling (PSAT) – Aymeric Rousseau and 3 staff
  - ✓ Market Potential and Penetration – Dr. Dan Santini and 3 staff
  - ✓ Fueling Infrastructure – Dr. David Livengood and 1 staff
- **Decision Sciences** – Dr. Richard Cirillo and staff
- **Geographic Information Systems –** Julie Muzzarelli and 11 staff
- **Infrastructure Assurance** – Dr. Ron Whitfield and staff
- **Electro-Chemical Engineering –** Dr. Jim Miller and staff
- **H2 and GHG Engineering –** Richard Doctor and 2 staff
- **Basic Science and Materials –** Dr. George Crabtree and staff
- **Nuclear Engineering –** Dr. Mark Petri and 5 staff

Skill Set – Models that Explicitly Include H2

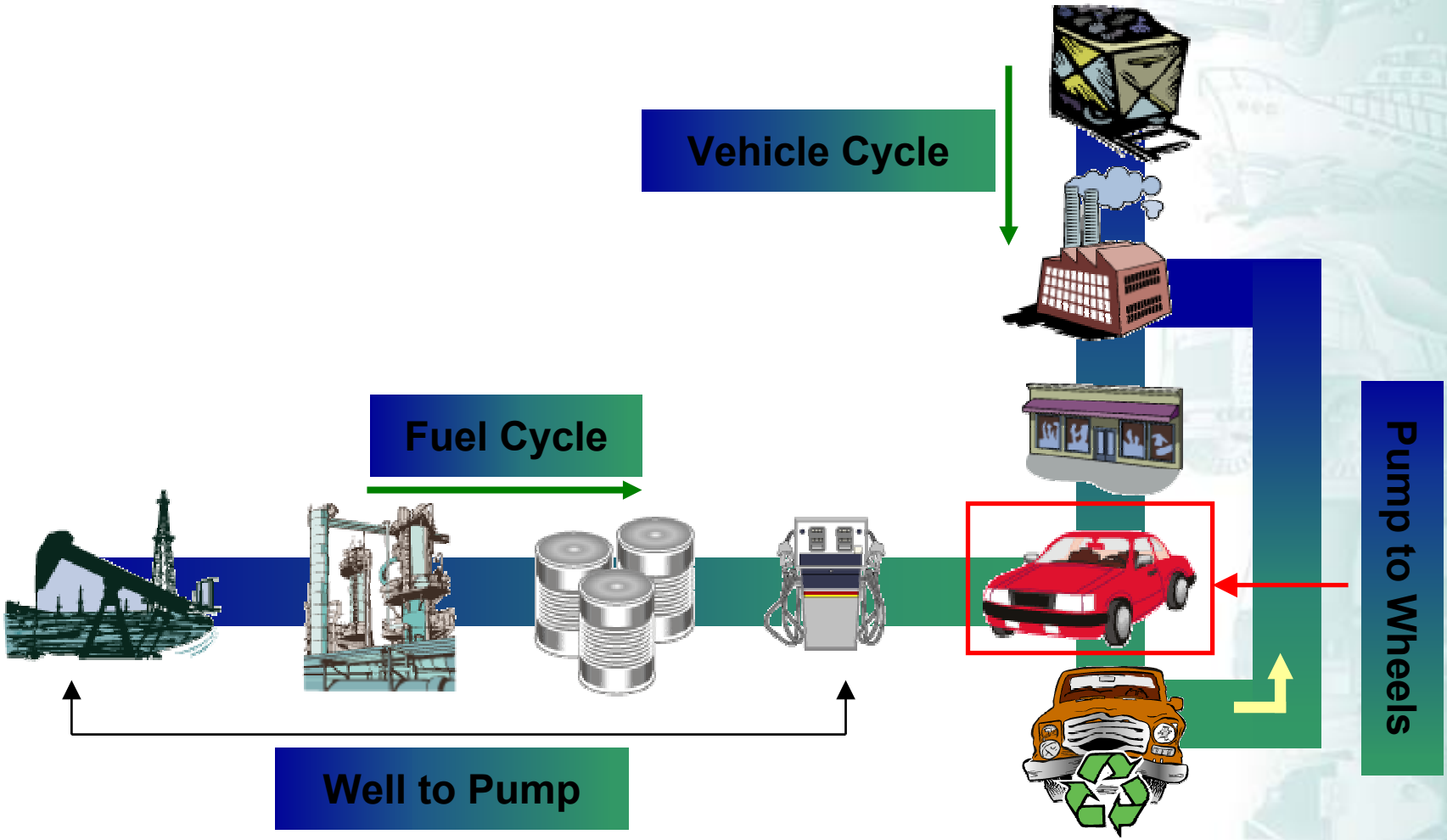
- H2A Delivery Scenario Generator
- GREET – life-cycle model of greenhouse gases and criteria pollutant emissions
- VISION – as explained by Phil Patterson
- CHAIN – H2 infrastructure cost model
- PSAT, GC-TOOL ENG – as explained by Lee Slezak
- Energy system models using agent-based and conventional modeling (ENPEP, EMCAS)
- AMIGA – general equilibrium model of the US economy
- Resource Analysis modeling – CTR and Nuclear groups

These models will be described in the following slides

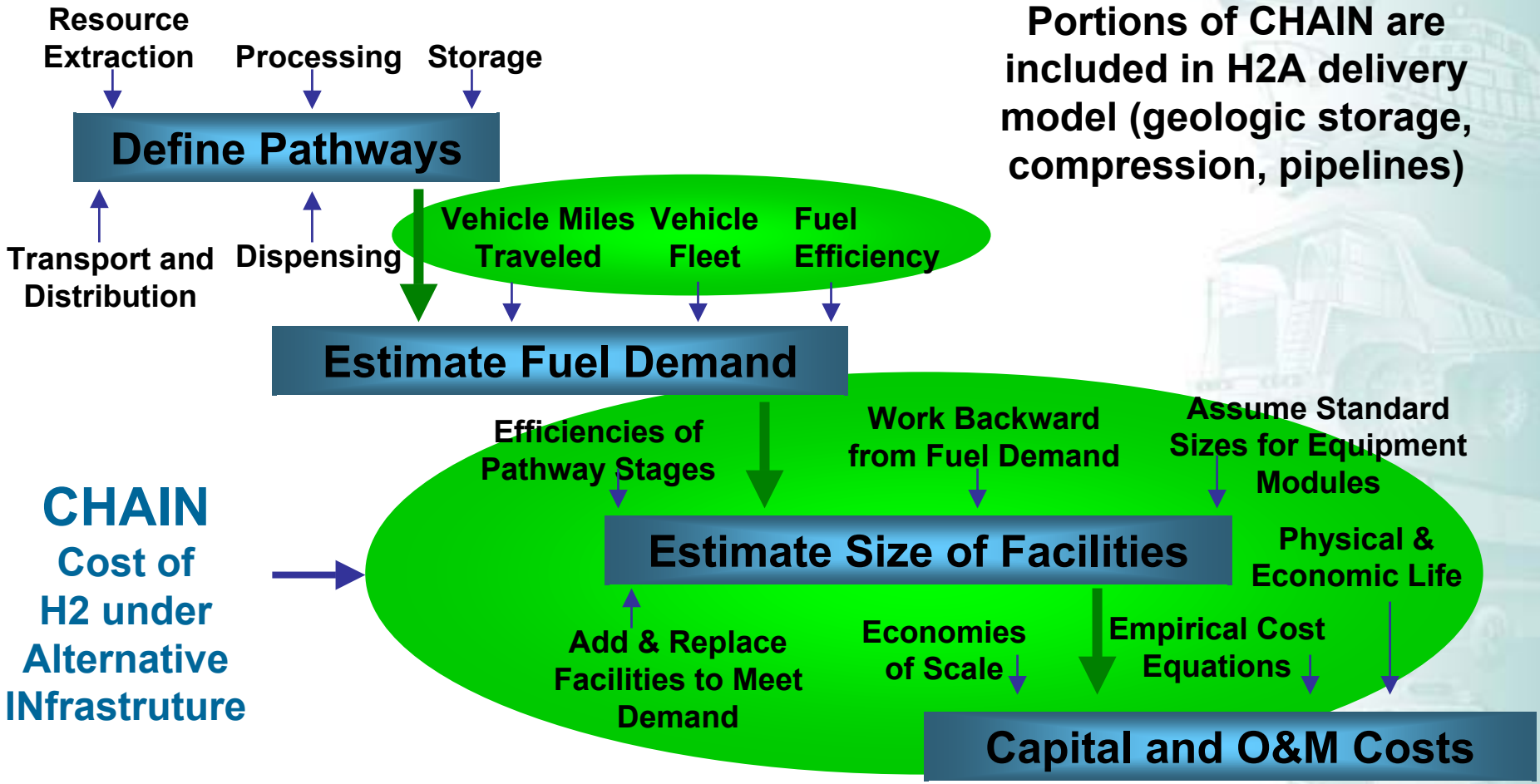
H2A Master Delivery Scenario Generator
(linked to Delivery Components Workbook)

- **Define configuration for each case and delivery mode.**
- **Calculate discounted cash flow across all components for each delivery scenario**
- **Calculate delivery component of hydrogen cost ($/kg) for each case. Delivery components include:**
  - Liquid hydrogen trucks
  - Compressed hydrogen gas trucks (tube trailers)
  - H2 compressors (single-stage)
  - H2 compressors (multi-stage)
  - Hydrogen pipelines
  - Liquefiers
  - LH2 storage tanks
  - Gaseous H2 storage cylinders
  - Compressed hydrogen gas terminals
  - Liquid hydrogen terminals
  - Gaseous H2 geologic storage

GREET Uses "Well-to-Wheels" (WTW) Analysis to Examine Fuels and Vehicles

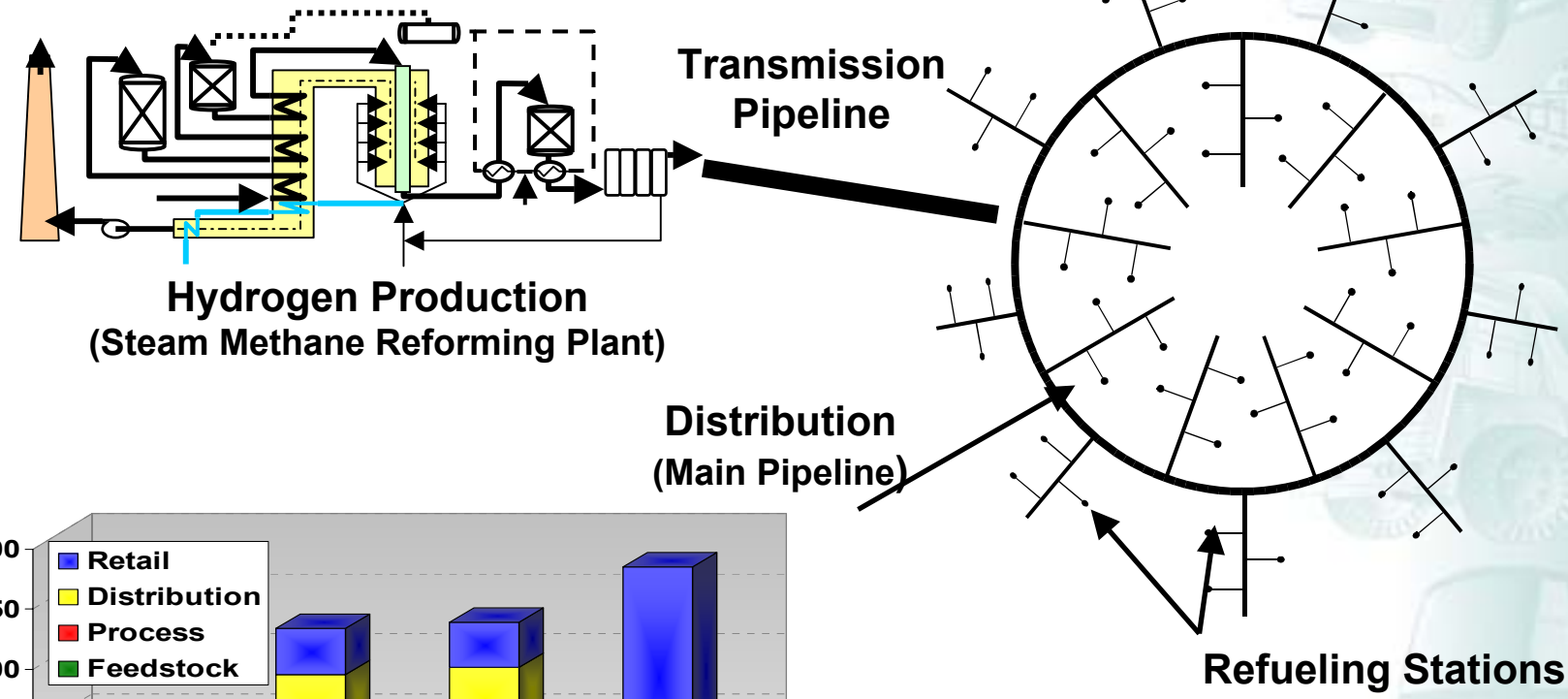


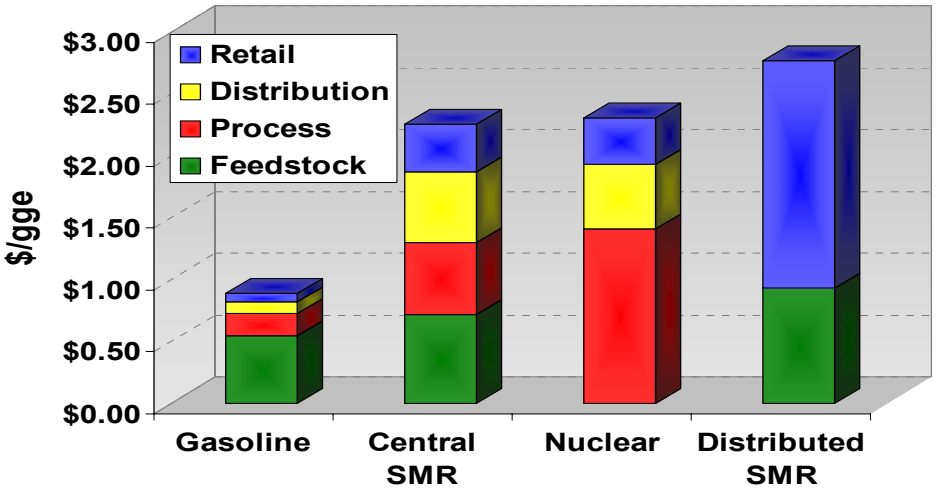
The CHAIN Model Estimates "Well-to-Pump" Levelized Costs of Hydrogen Infrastructure



Portions of CHAIN are included in H2A delivery model (geologic storage, compression, pipelines)

CHAIN Model Focuses on Gaseous H2 Production and Pipeline Distribution





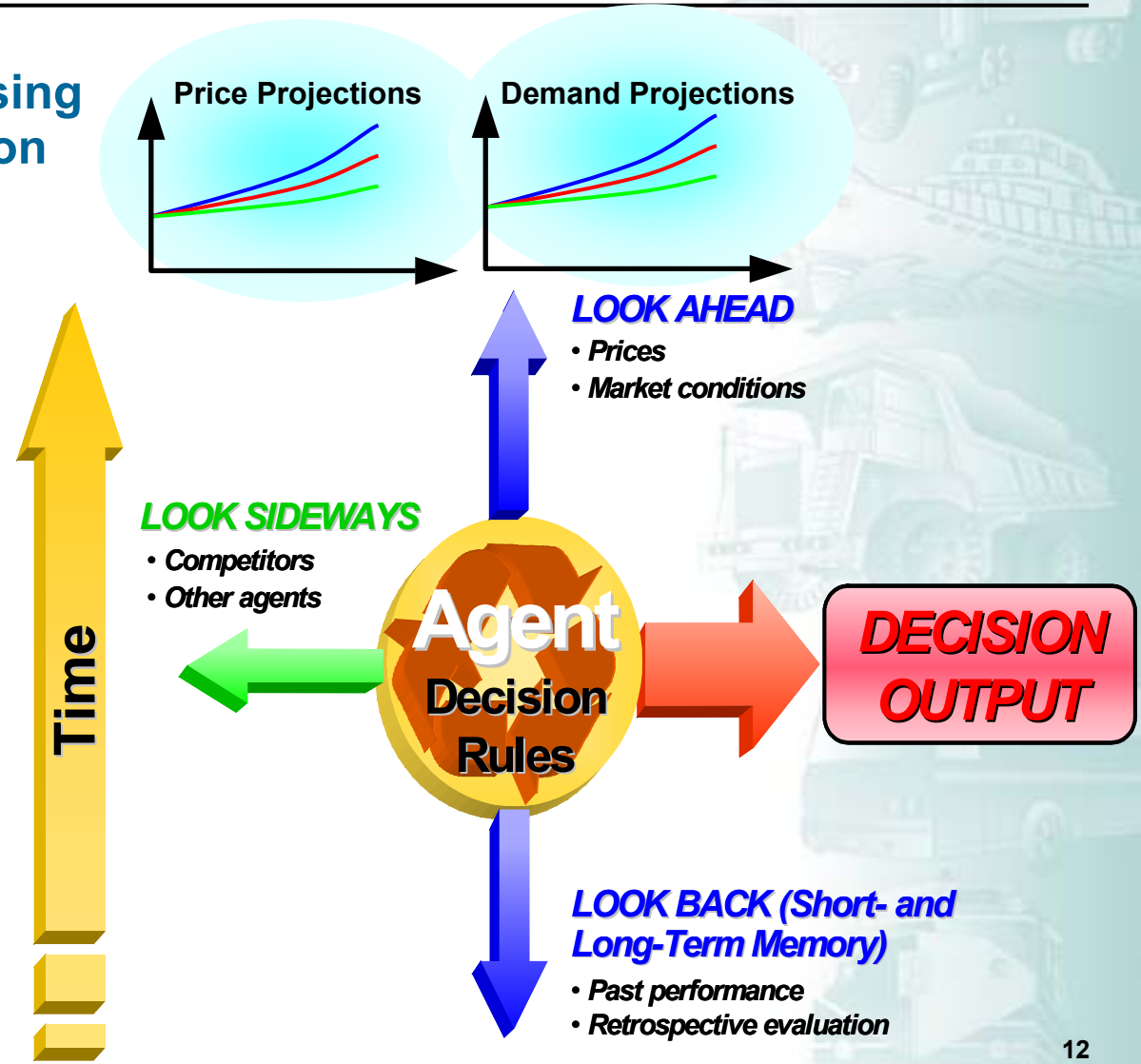
Processing, distribution and retailing account for 75-100% of H2 levelized cost vs <40% for gasoline. (2050 Study)

Agent-Based Complex Adaptive Systems: Intuitively Appealing Method to Analyze Large Energy Systems

- Complex adaptive systems consist of numerous heterogeneous entities (players) that interact with each other and their environment often in non-linear ways, adapt to change and evolve their behavior
- Agent-based modeling and simulation (ABMS) simulates the behaviors and interactions of large numbers of entities (*agents*) and studies the macro-scale consequences of those interactions

H_2/Energy Market Agents Consider Information on the Past, Present, and Future in their Decisions

- Agents make decisions using local and public information
- Agents develop price expectations by market segment or region
- Agents develop demand scenarios by market segment/region
- Agents consider actions of competitors
- Agents consider past performance in making their decisions

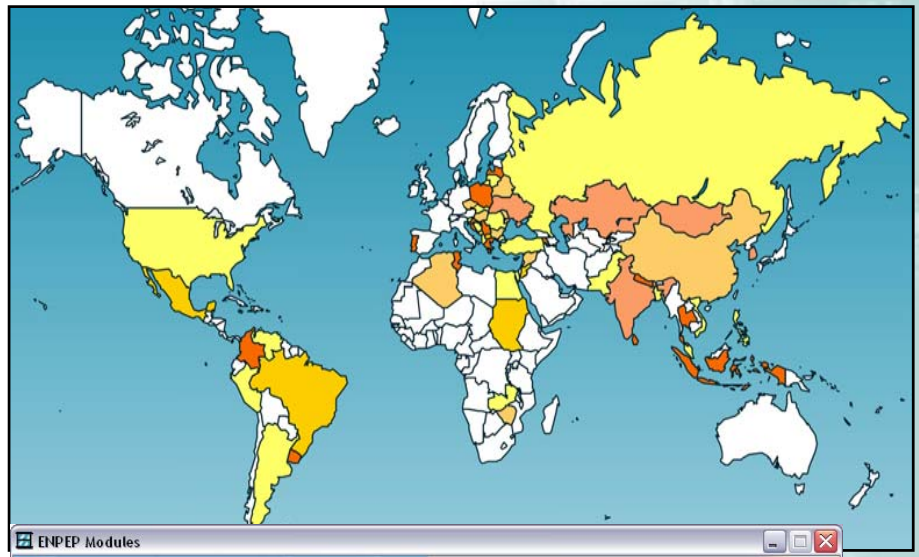


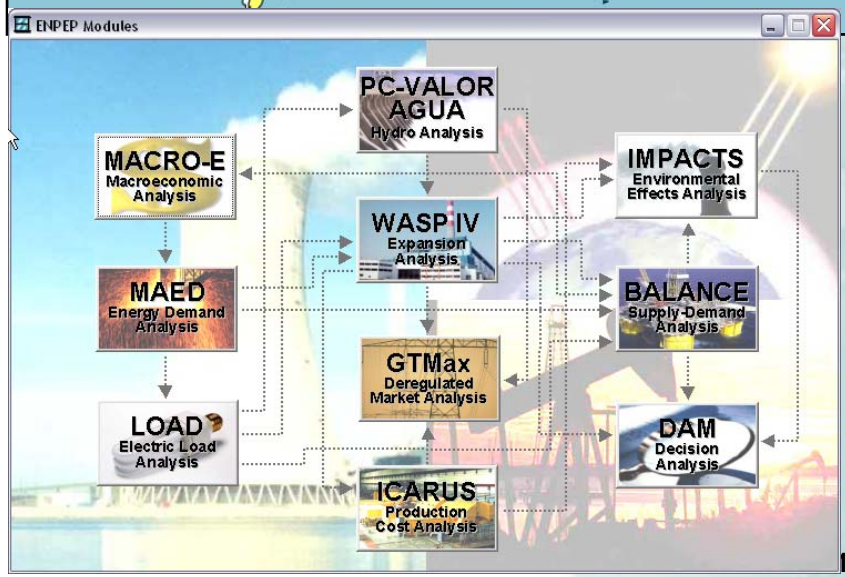
Agent-Based CAS Models Have Key Advantages

- **New insights into H_2 infrastructure development issues**
  - ✓ Better represent uncertainty and volatility
  - ✓ Improved modeling of heterogeneity of market participants
  - ✓ Better understanding of transition/inflection points and their causes and drivers
- **Platform for**
  - ✓ Testing different business models/strategies, policies/market rules
  - ✓ Defining scenarios
  - ✓ Examining co-evolution of H2 demand and supply infrastructure

ANL's Energy and Power Evaluation Program (ENPEP) is Used around the World for Energy Policy Analyses

- Overall energy sector development strategies and hydrogen transition analysis
- Natural gas market analysis
- Energy conservation, efficiency, demand-side management
- Economics of renewables
- Emissions projections for PM, SO_2, NO_X, etc.
- Emissions reduction strategies for PM, SO_2 and NO_X
- Emissions trading for SO_2 and CO_2 (cap and trade) and emissions taxes
- GHG mitigation studies and Kyoto Mechanisms



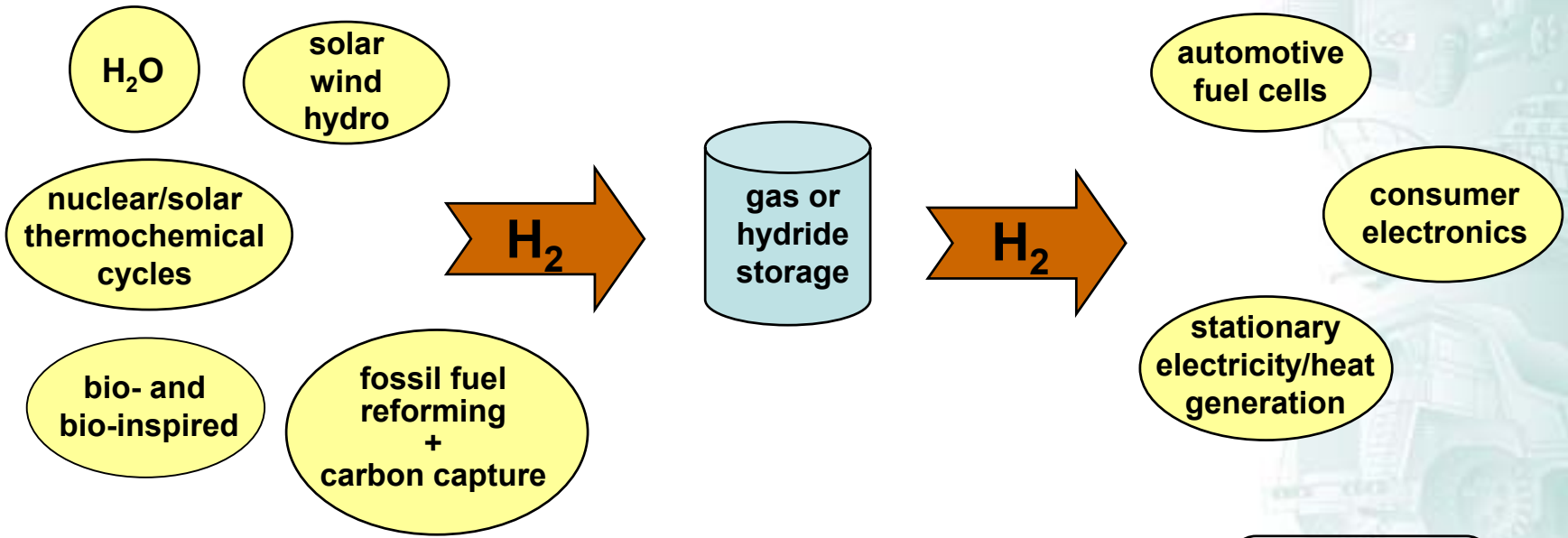


Argonne and NETL Have Teamed to Study Transition Paths to a Hydrogen Economy

- **Transition analysis includes both fuels and vehicles:**
  - ✓ Advanced vehicles with hybrid capability
  - ✓ Increased refinery production of hydrogen to upgrade transportation fuel quality
  - ✓ Analysis of coke and coal gasification at refineries for electricity production, process heat, and Fischer-Tropsch blendstocks
  - ✓ Integrated economy & energy market simulations using Argonne's AMIGA model (a calculable general equilibrium model)

- **The Argonne/NETL study involves**
  - Improved refinery sector modeling, including upstream and downstream effects
  - Refinery impacts of transition scenarios to hydrogen
  - Refinery applications of coke and coal gasification technologies

The Hydrogen Economy – Resource Analysis



9M tons/yr

150 M tons/yr
(light trucks and cars in 2040)

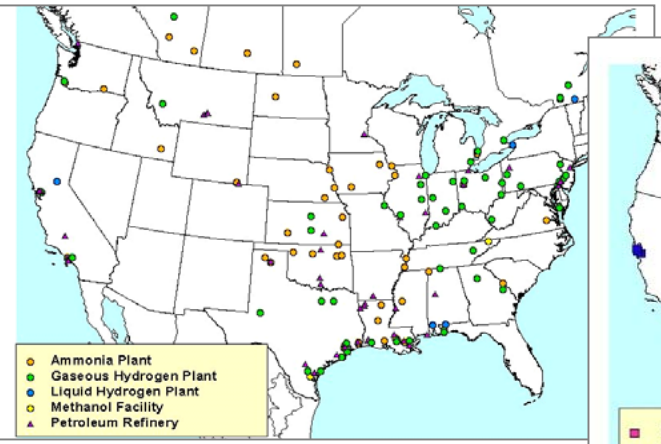
4.4 MJ/L (Gas, 10,000 psi)
8.4 MJ/L (LH2)

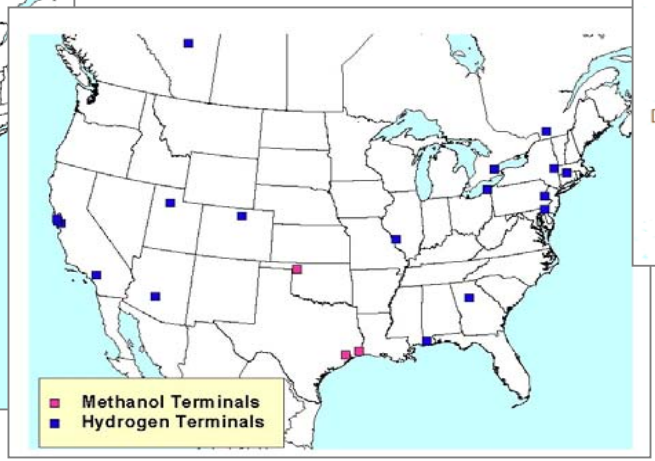
9.72 MJ/L
(2015 FreedomCAR
Target)

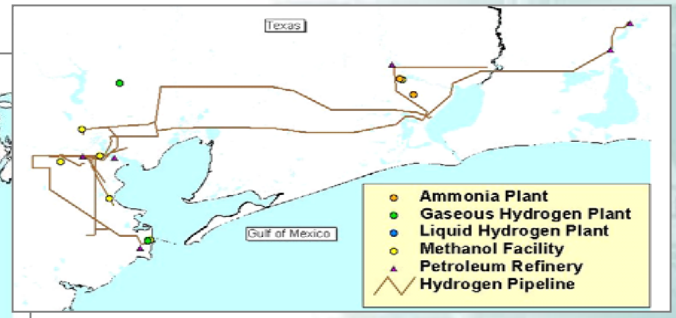
$3000/kW

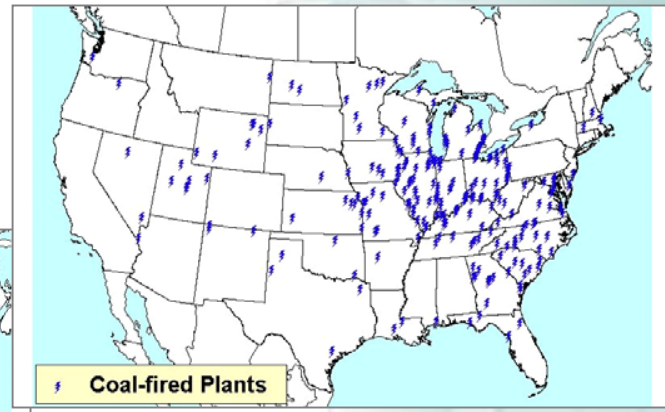
$35/kW
(Internal Combustion Engine)

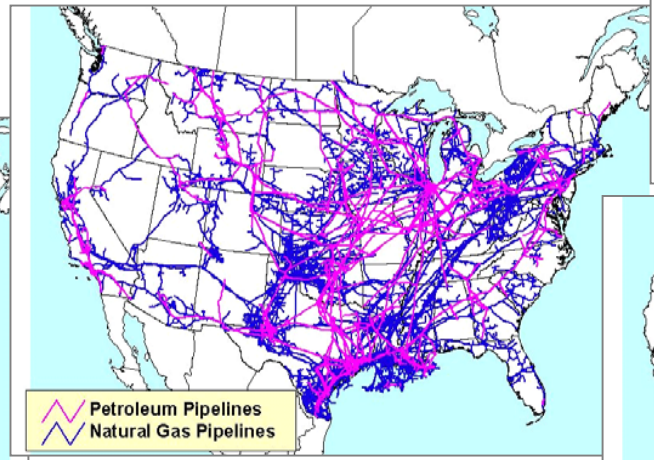
GIS Are Used to Plot Potential Hydrogen Infrastructure and Resources

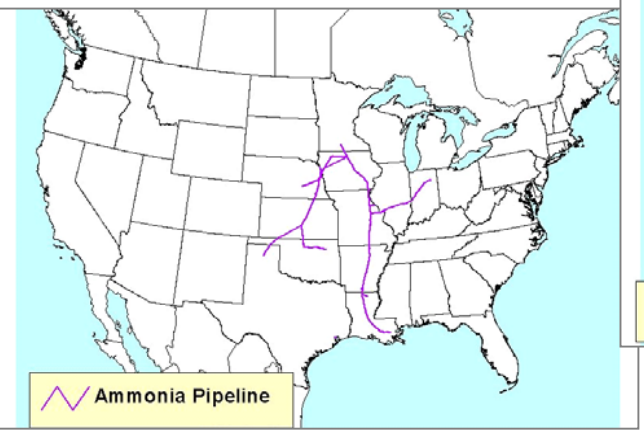


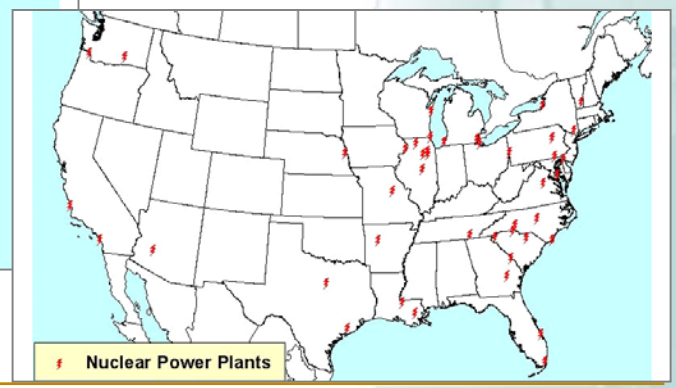




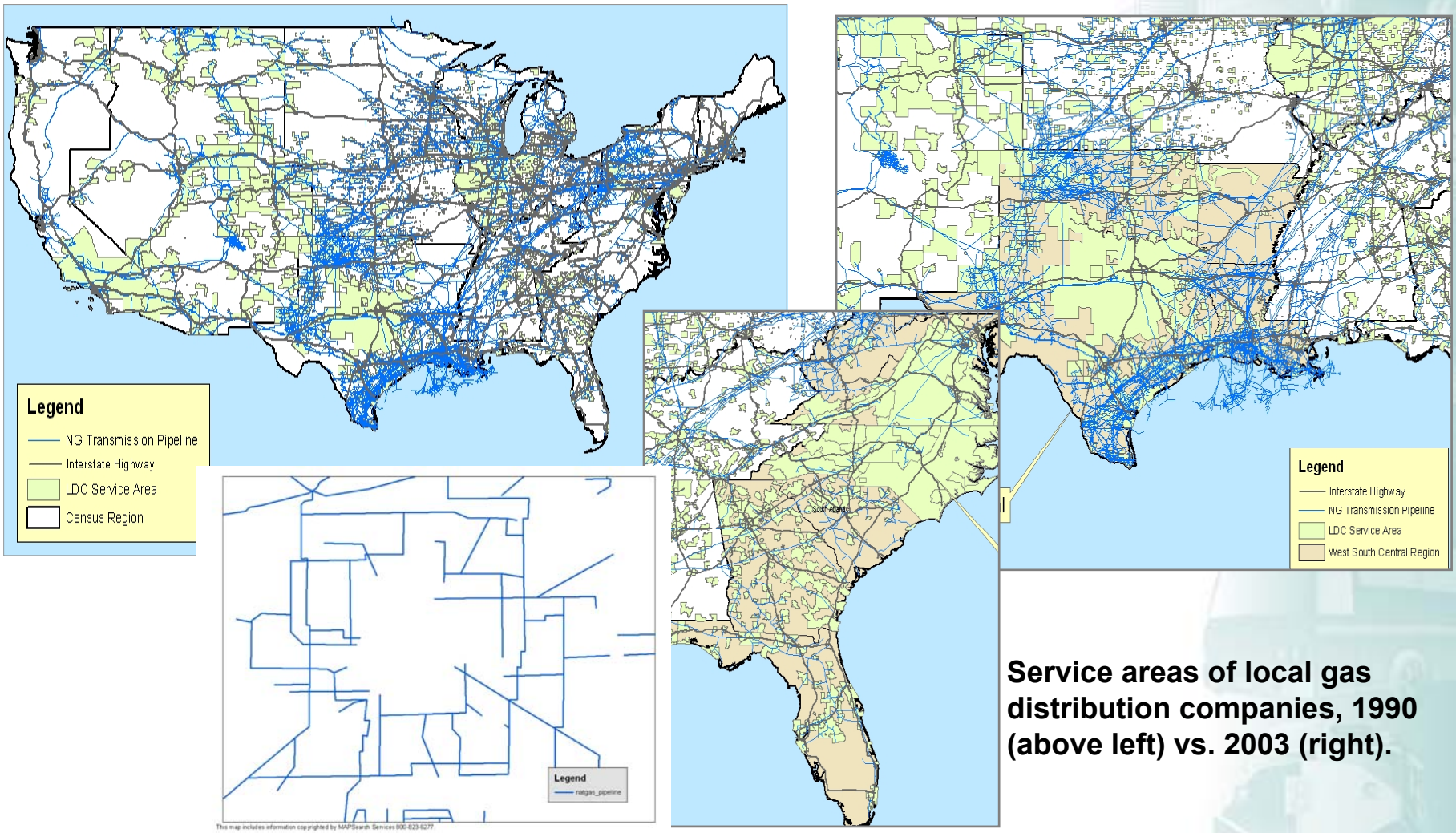








To Validate Model Results, and to Identify Regional Opportunities and Data Gaps



Service areas of local gas distribution companies, 1990 (above left) vs. 2003 (right).

ANL Skill Set – Capabilities Summary

TYPE OF ANALYSIS	RESIDENT CAPABILITY?	STUDIES SPECIFIC TO H_2?	MODELS SPECIFIC TO H_2?
Resource Analysis	***Yes***	***Yes***	***No – use comprehensive approach***
Techno-economic Analysis	***Yes***	***Yes***	***No – use comparative approach***
Environmental Analysis	***Yes***	***Yes***	***No – use integrated, systematic approach***
Delivery Analysis	***Yes***	***Yes***	***Yes***
Infrastructure Development Analysis	***Yes***	***Yes***	***Yes***
Energy Market Analysis	***Yes***	***Yes***	***No – use comprehensive approach***

ANL Hydrogen Studies

- *List significant past studies that relate to hydrogen – see separate handout*

- *Current/planned hydrogen studies:*
  - ✓ H2A delivery infrastructure characterization and modeling (incl terminals, pipelines and geologic storage)
  - ✓ GREET expansion
  - ✓ Expansion and application of CHAIN model to SE US.
  - ✓ Support to BPA/Phil Patterson on market penetration, transition issues and regional analysis
  - ✓ Support to Vehicle Systems/Lee Slezak on improved vehicle simulations, and sub-system and vehicle validation
  - ✓ Internal work on agent-based modeling of H2 as a CAS
  - ✓ Hydrogen and oxygen market analysis for nuclear H2 production
  - ✓ GIS of potential H2 production, distribution facilities and ROW
  - ✓ ANL/NETL H2 transition scenario analysis
  - ✓ Fuel transitions analysis

ANL's View of Its H2 Analysis Future

- ANL plans to continue and modestly expand our analytic capabilities in the hydrogen area
- ANL will continue to forge strong partnerships with super major oil companies, hydrogen suppliers, universities and vehicle manufacturers to stay abreast of technology developments for H2 production, distribution, and utilization
- ANL will continue to build upon its reputation for objective analysis in support of our sponsors and customers

Backup Slides

Analysis Issues

- ***Open podium – what do you see as the major issues related to analysis of hydrogen systems?***

Types of Hydrogen Analysis

Resource Analysis
–Where are the resources to make hydrogen and how much do they cost?

Technology Feasibility and Cost Analysis
–Which technologies have the greatest potential for economic success?
–Where should research efforts be focused?
–What are the impacts of production volume?

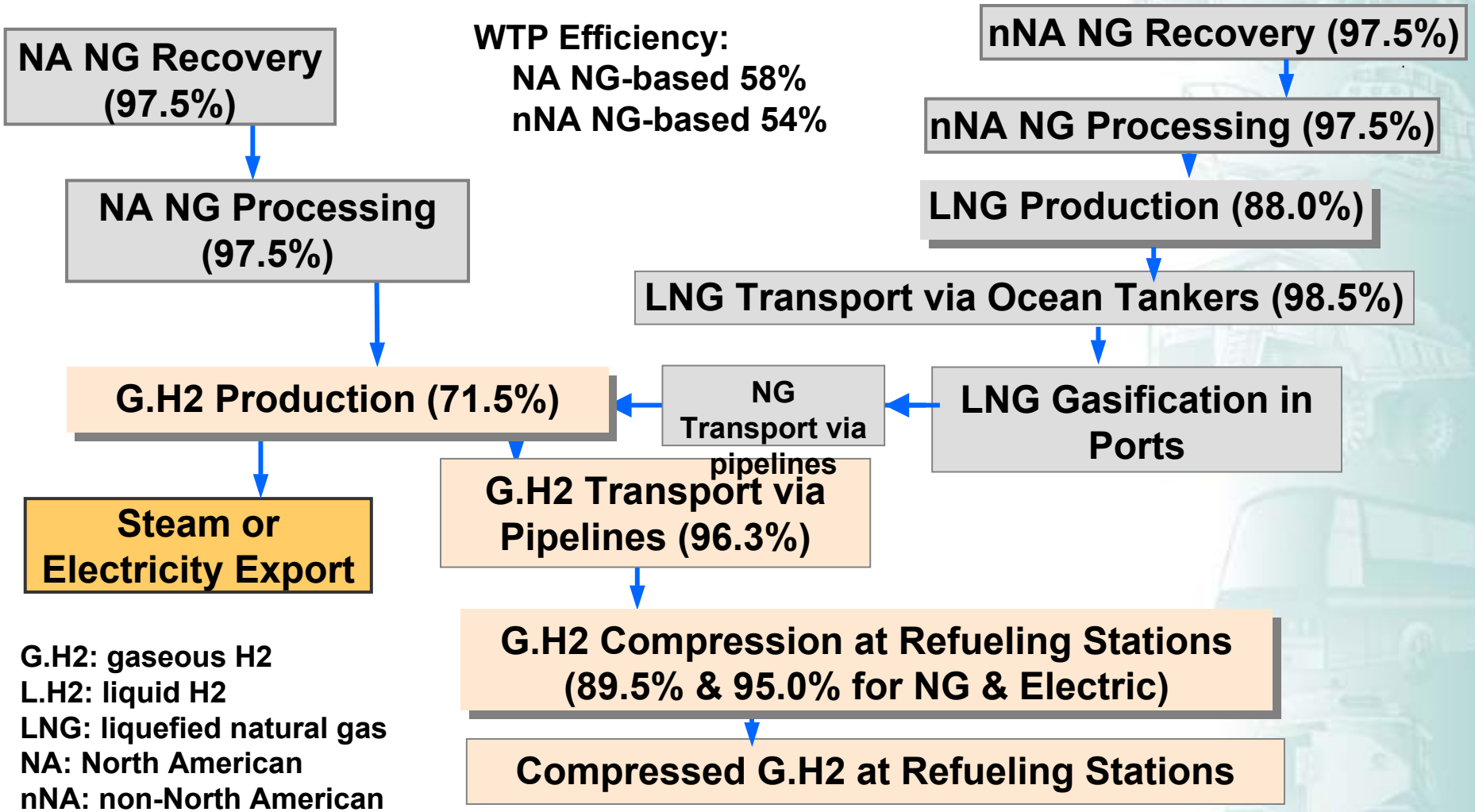
Environmental Analysis
–What are the environmental impacts of hydrogen technologies?
–What steps can be taken to reduce impacts?

Delivery Analysis
–What are the most economic options for delivering hydrogen?

Infrastructure Development and Financial Analysis
–What are the optimal scenarios for developing the hydrogen infrastructure?
–What will a hydrogen infrastructure cost and what are the financial risks?

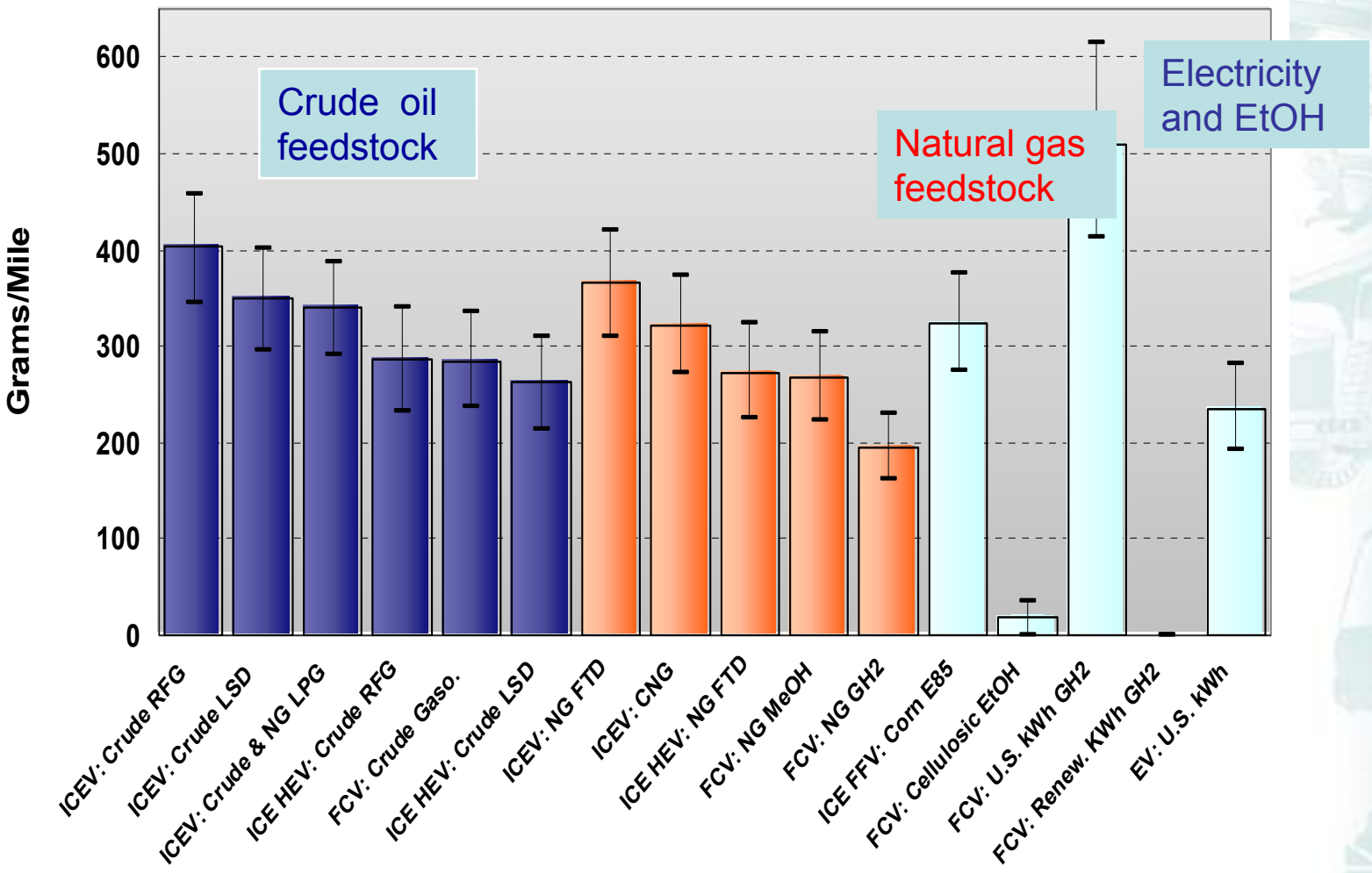
Energy Market Analysis
–What are feasible hydrogen futures?
–Which technologies are most likely to be a part of the hydrogen future, and what are the interactions between hydrogen and other energy carriers?
–What are the scenarios for hydrogen use in transportation and stationary markets?
–What are the impacts, costs, and financial risks?
–What market penetration pathways are likely?

Production and Compression Are Key Steps for Gaseous H_2 Production



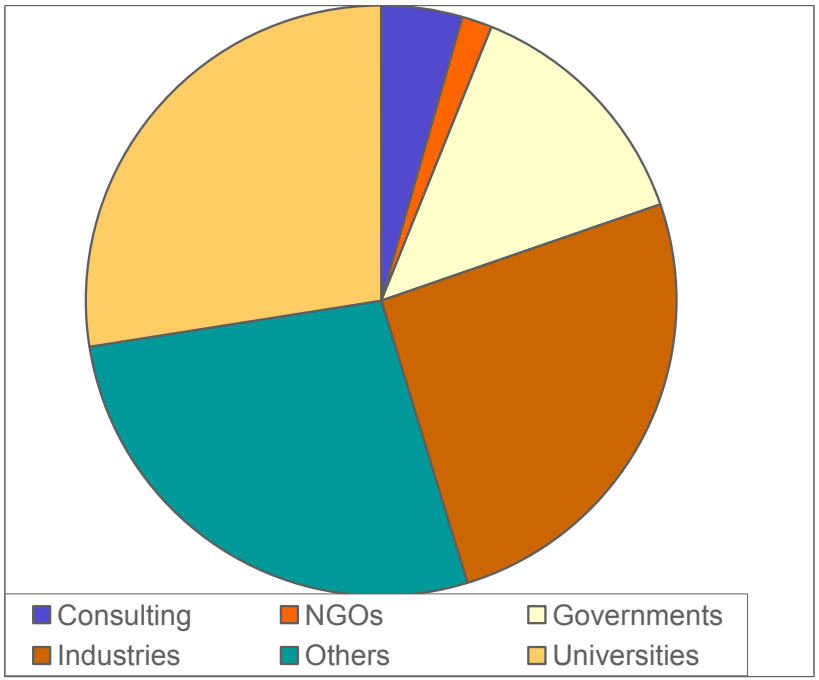
G.H2: gaseous H2
L.H2: liquid H2
LNG: liquefied natural gas
NA: North American
nNA: non-North American
NG: natural gas

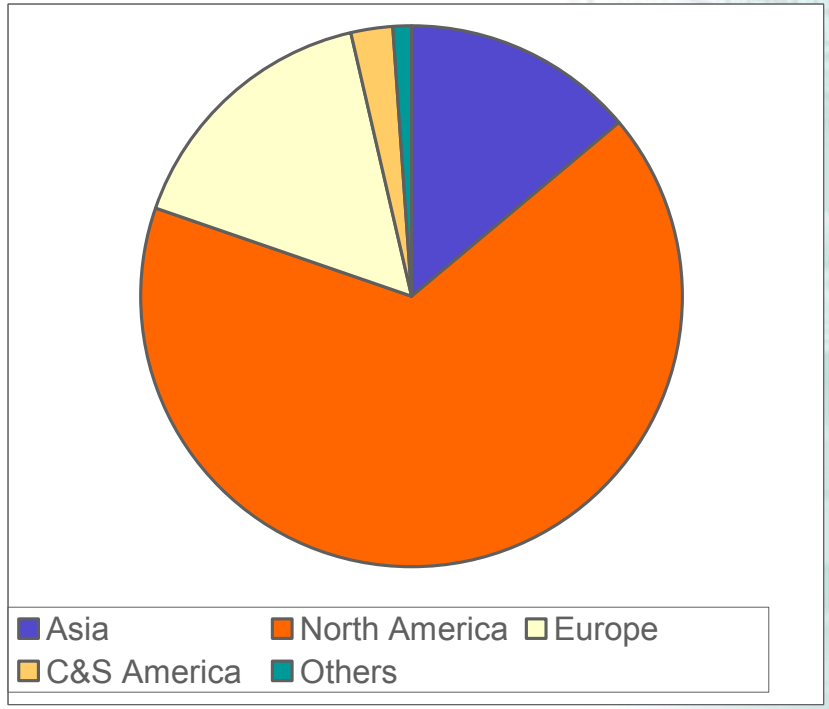
WTW GHG Emissions of Selected H2 Pathways Relative to Other Pathways



The GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) Model

At Present, There Are > 1,200 GREET Registered Users Worldwide

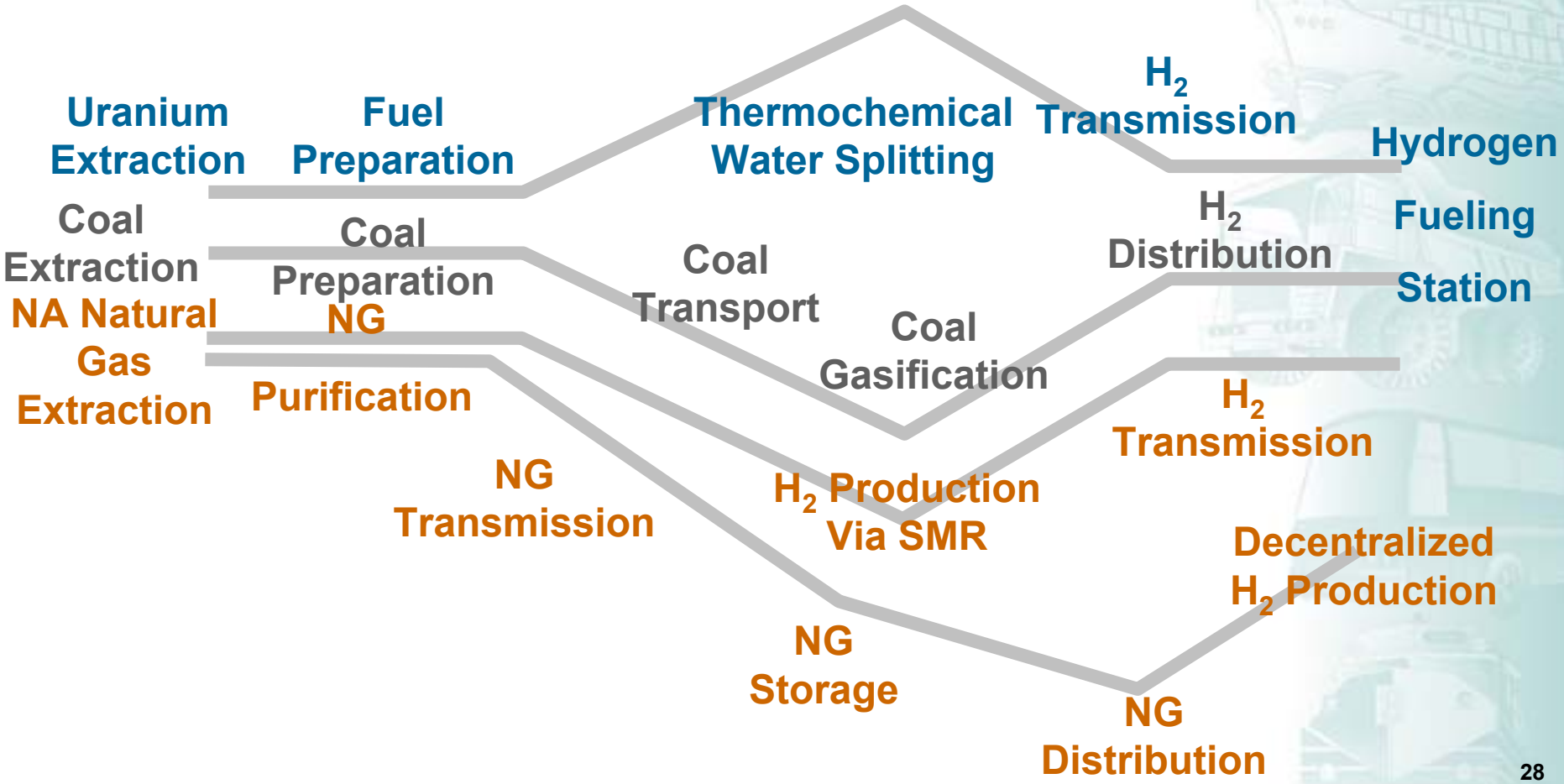




The GREET model and its documents are available at

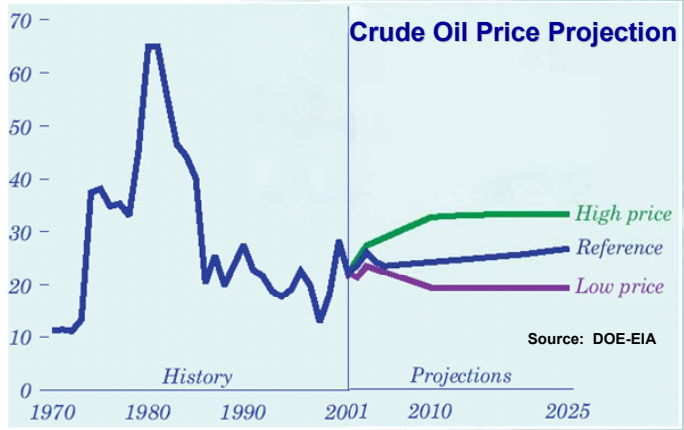
http://greet.anl.gov

Hydrogen Pathways Modeled by the CHAIN Model for 2050 Study

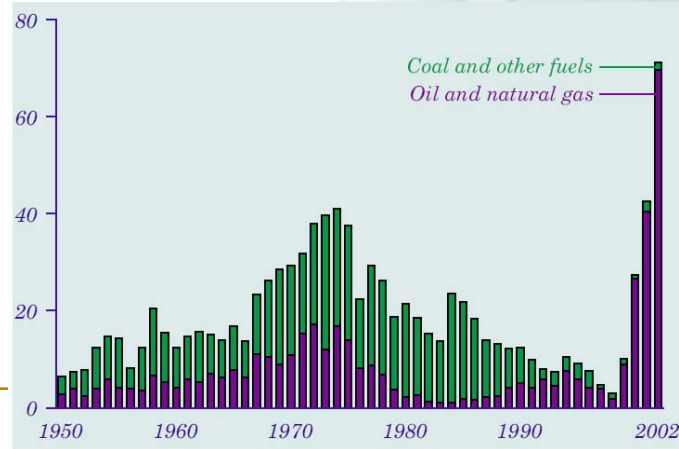


Current Energy Systems Models Do Not Adequately Capture Underlying Complexities

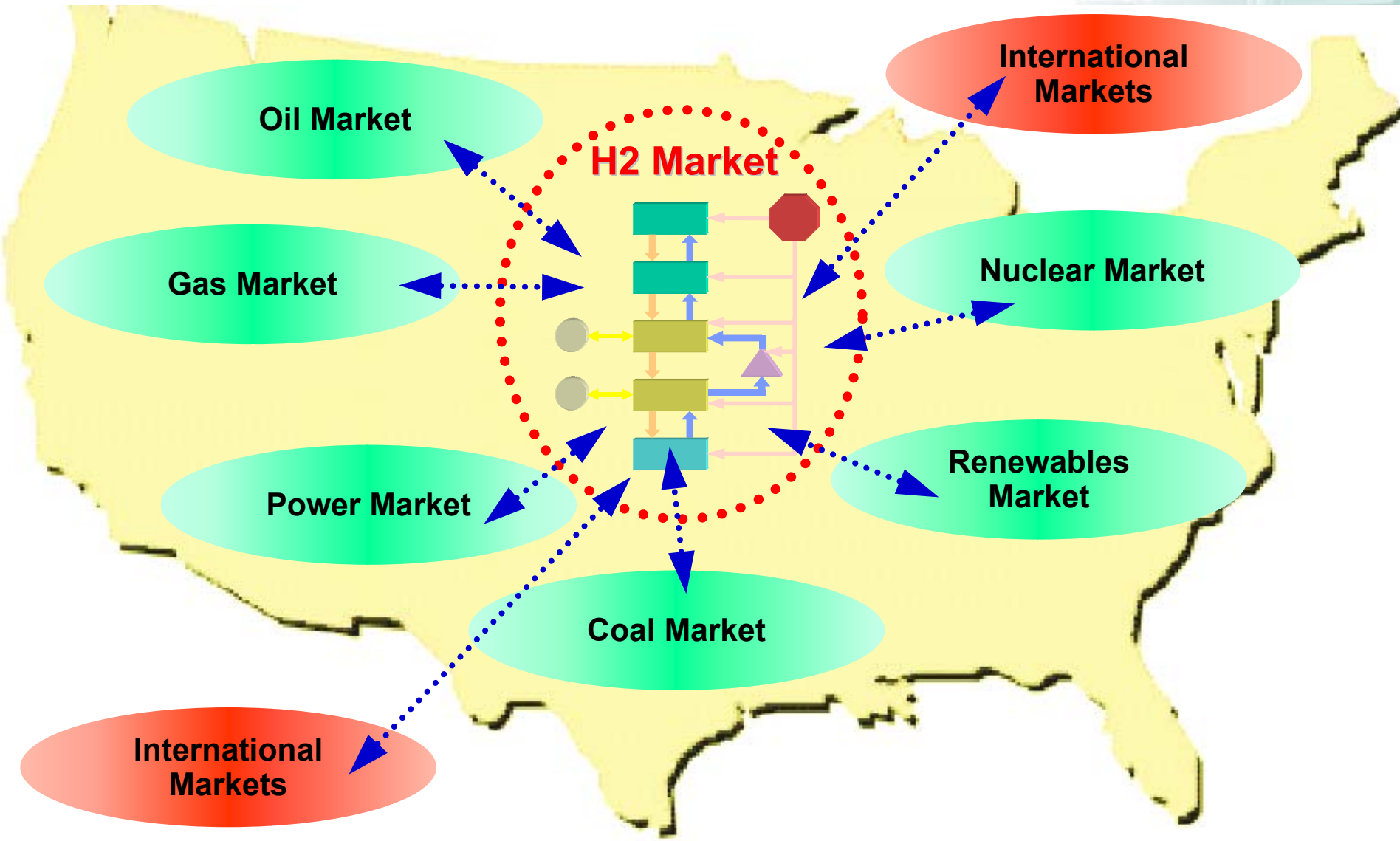
- **Existing simulation and optimization tools are limited in accounting for volatility and uncertainty prevalent in today's energy markets**
  - ✓ Single decision-maker
  - ✓ Perfect foresight
  - ✓ Rational decision-making
  - ✓ Energy markets in equilibrium



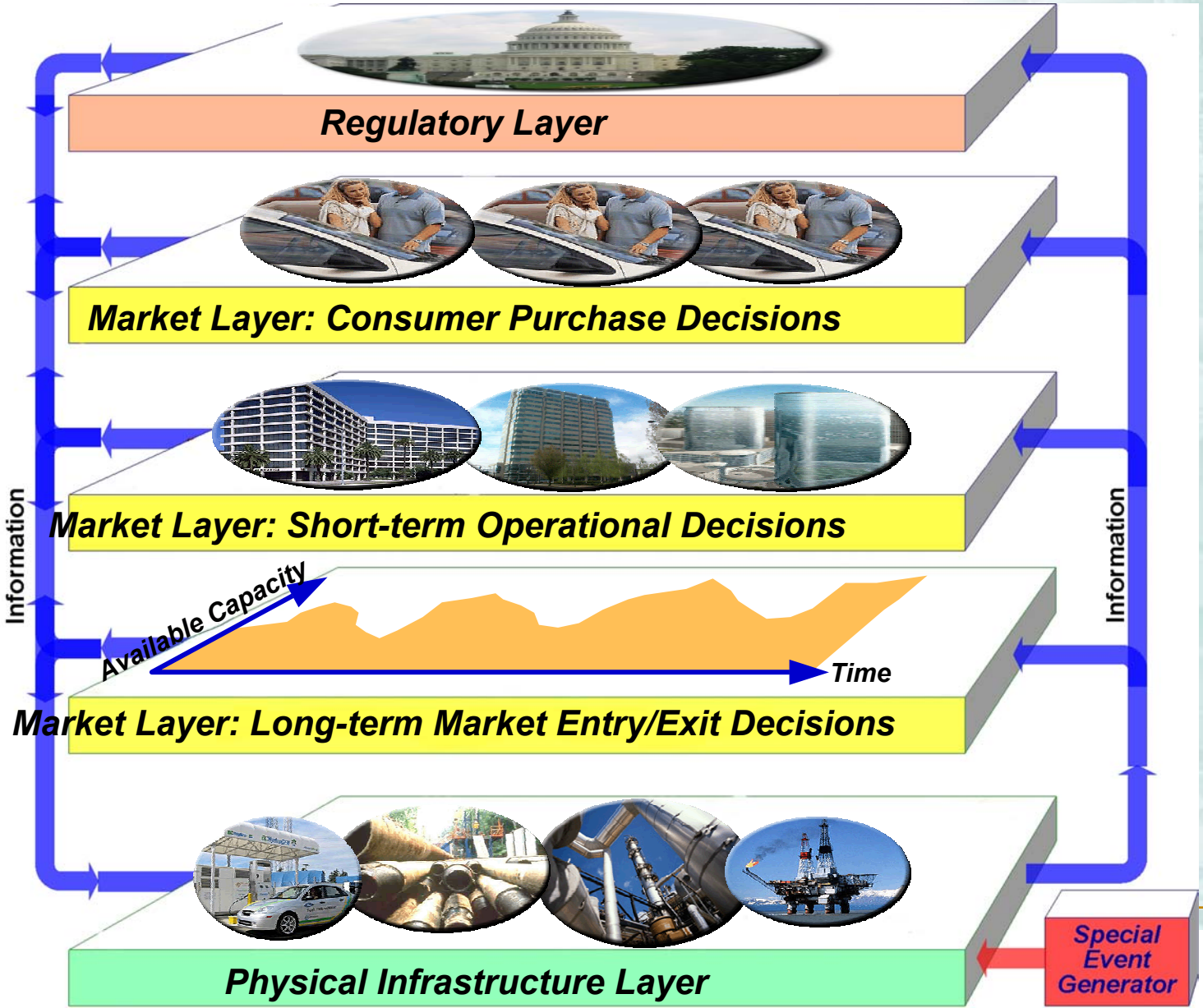
- **Straight-line projections ignore dynamics, uncertainties, potential for sudden shocks and disruptions, market imperfections, and emerging strategies by market participants**
  - ✓ California power restructuring
  - ✓ Recent crude oil & natural gas price volatility
  - ✓ Rush to natural gas for power generation and recent collapse



Complexity Increases If H_2 Market is Modeled as Part of the Larger Energy Market

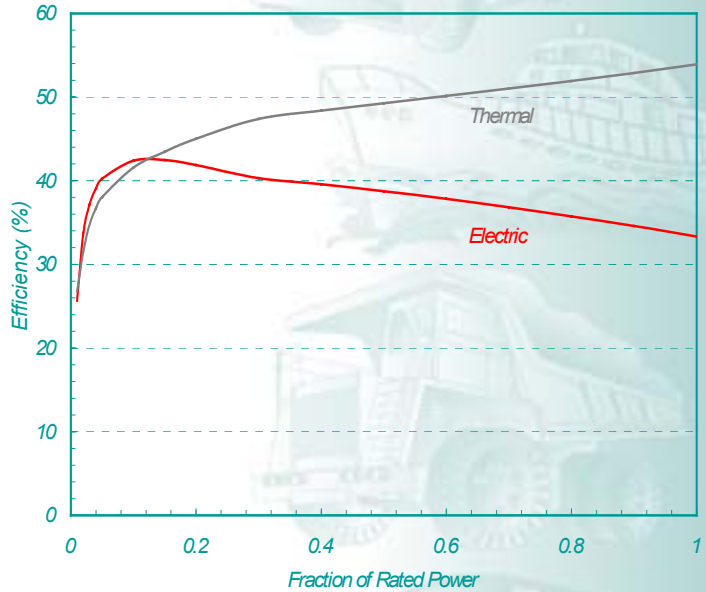


H_2/Energy Market Agents Make Decisions in a Complex and Multidimensional Environment



GCtool:
Fuel Cell Systems for Combined Heat and Power

- Mismatch between thermal and electric demands.
- Summer: High electric but low thermal demand
- Winter: Low electric but high thermal demand



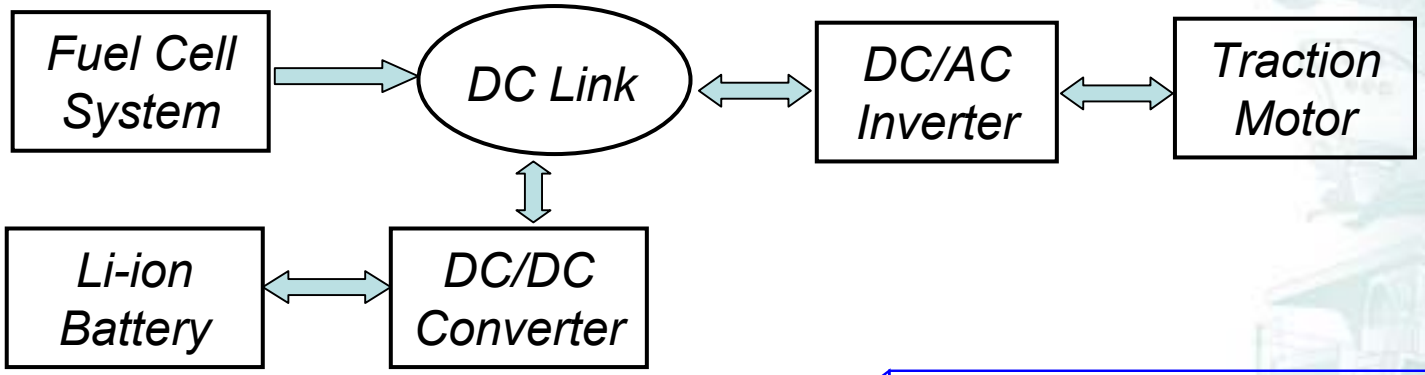
Why heat pump with FC-CHP makes sense?

- Natural gas (NG) furnace, ¢2/kWh ($0.60/therm)
- Heat pump (HP) with central power (CP), ¢8/kWh
- Heat pump coupled with fuel cell system (FCS)

Ambient Temp		Thermal Efficiency			Relative Energy Cost		
	HP	NG	CP+HP	FCS+HP	NG	CP+HP	FCS+HP
°C	COP	%	%	%	$	$	$
10	3.6	80	119	171	100	86	47
0	3.0	80	100	152	**100**	**103**	53
-10	2.5	**80**	**81**	133	100	126	60
-20	2.2	80	71	123	100	145	65

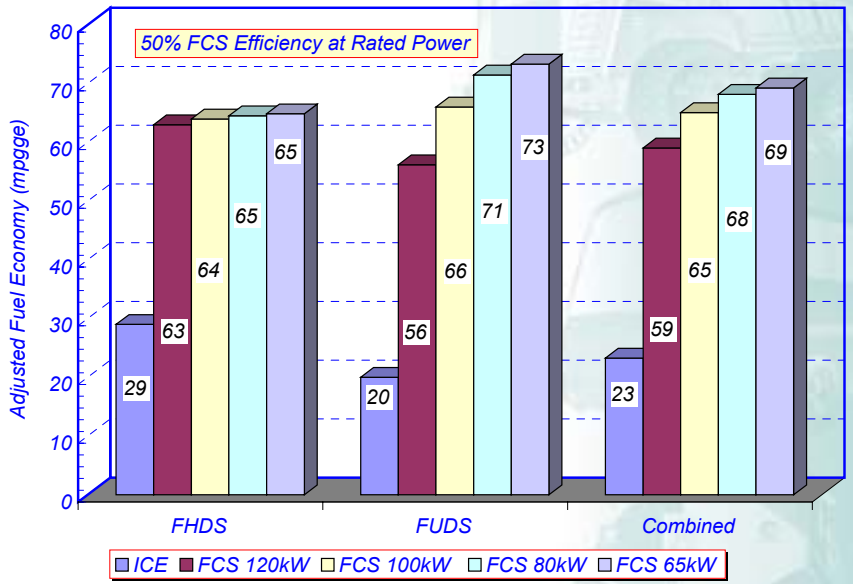
GCtool_ENG and PSAT
Fuel Economy of Hybrid Fuel Cell Vehicles

GCtool-PSAT model of load-following fuel cell vehicles

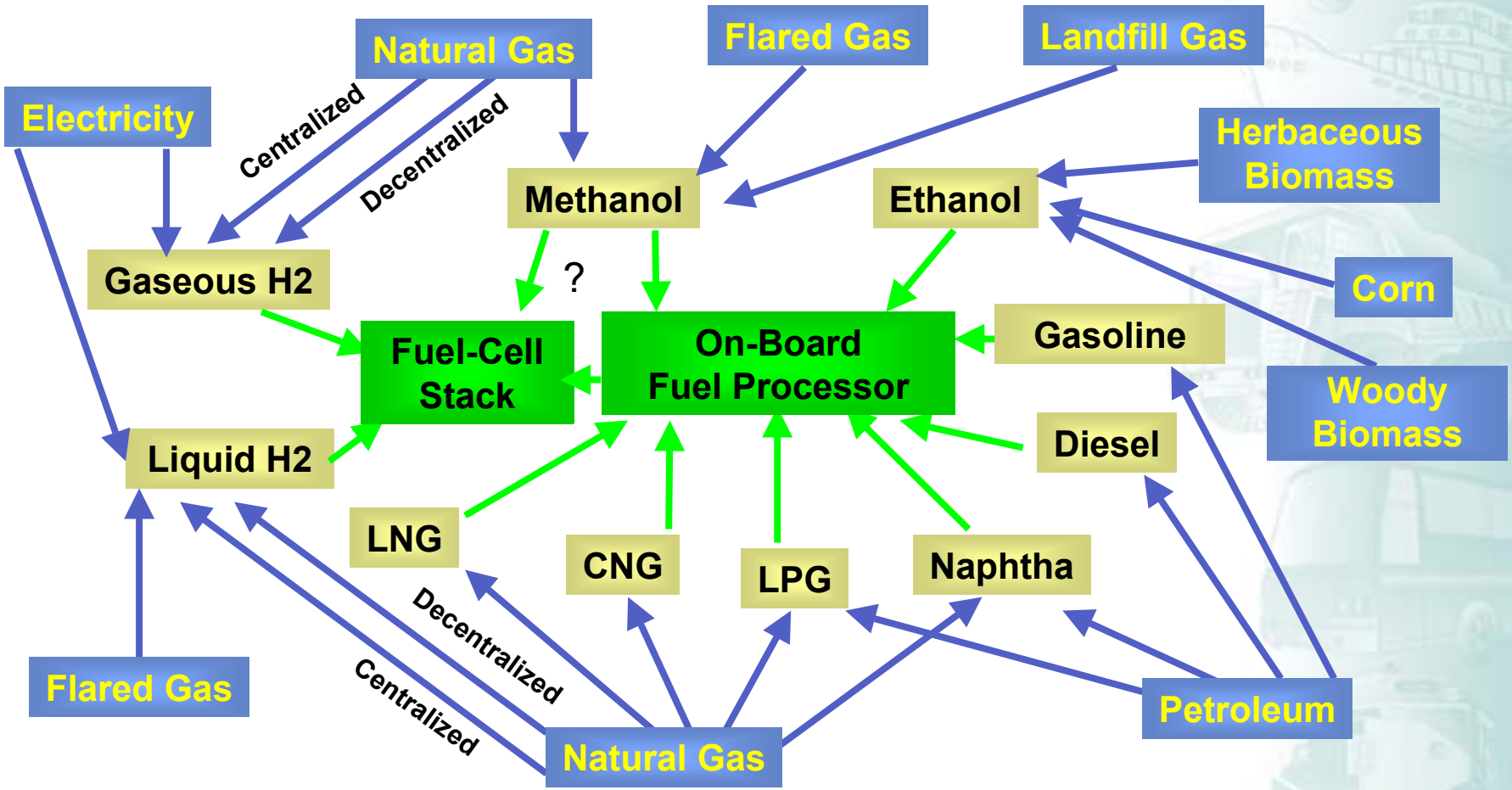


Results for mid-size family sedan

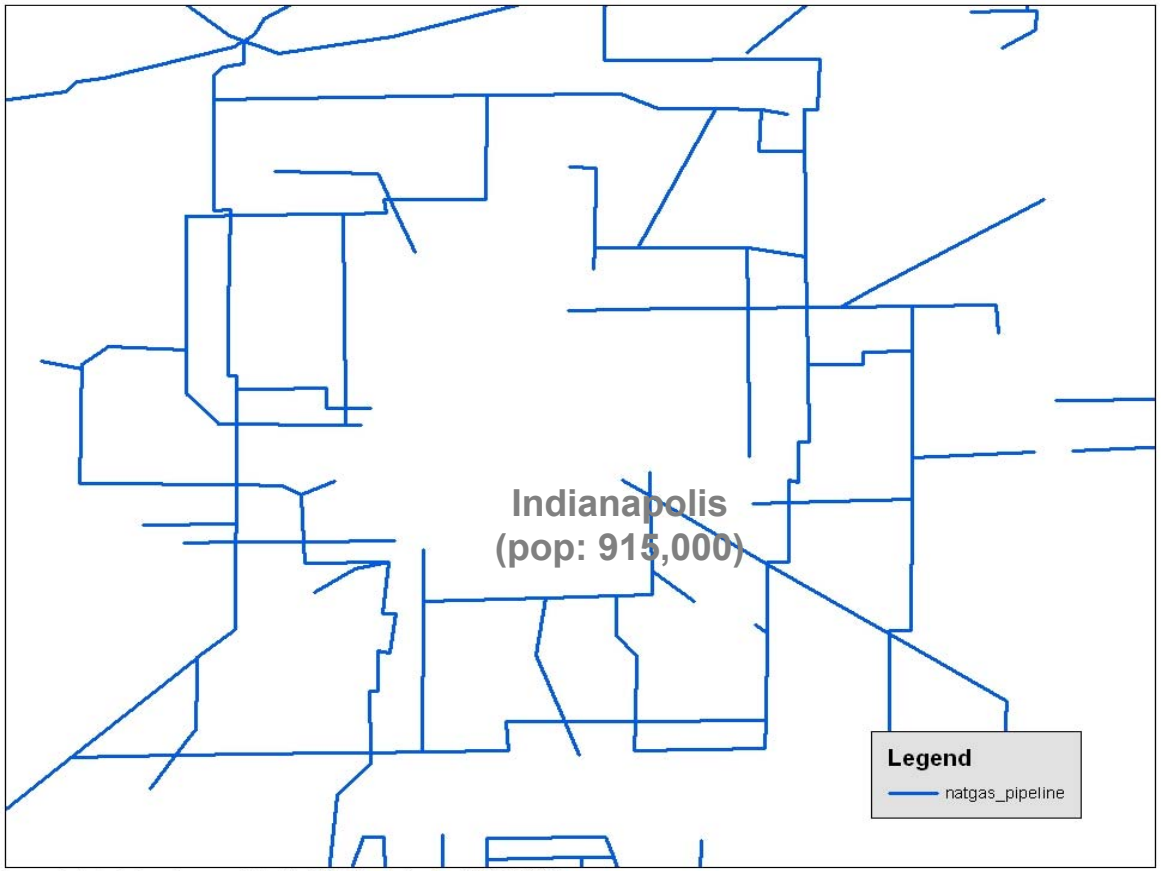
- 65-kW sustained at 100 mph
  120-kW peak for Z-60 in 10s
- FCS/ICE FE multiplier
  3.0 with 55 kW ESS vs. 2.5 with stand-alone FCS



GREET Examines Many Fuels and Fuel Pathways



Generic Geometry Compares Well with Observed NG Pipe Geometry for Similar-Sized Urbanized Area



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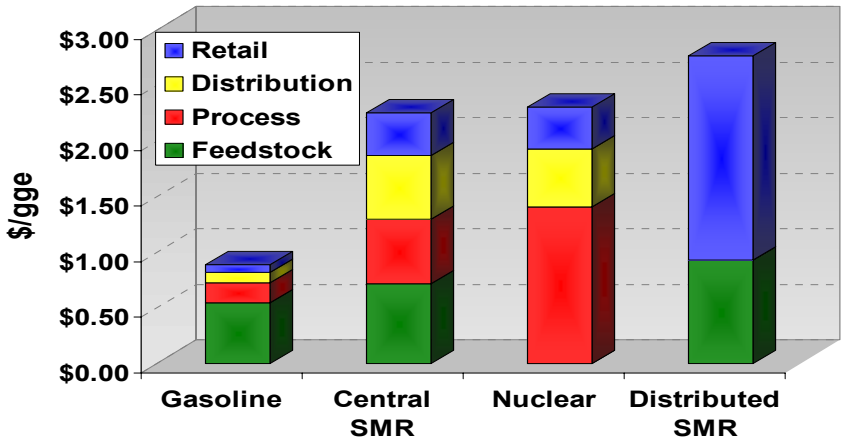
Skill Set – Models

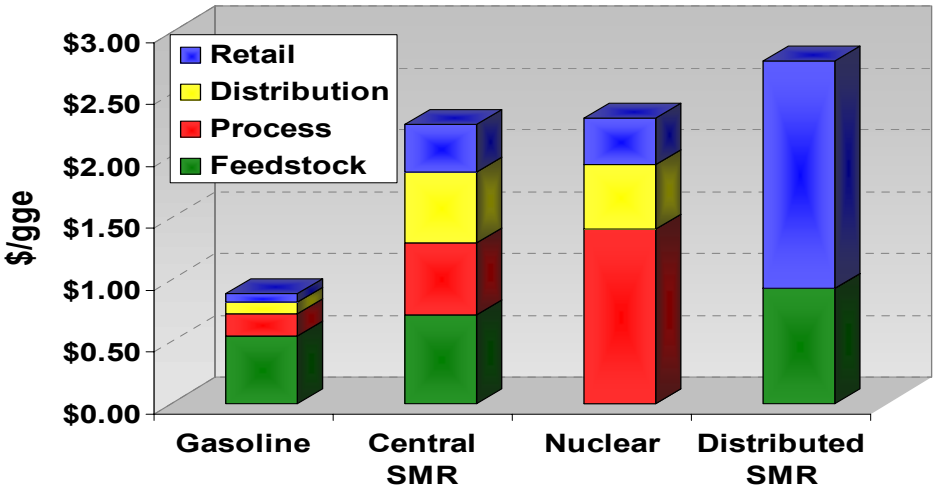
(add slides as necessary)

- ***List models that explicitly include hydrogen***
  - *Model name, dates in use, brief description*
  - *Modeling methodology (e.g., linear programming, thermodynamic, etc.)*
  - *Model platform (e.g., GAMS, ASPEN, etc.)*
  - *Model limitations*

- ***List models that could be adapted to include hydrogen***
  - *Model name, dates in use, brief description*
  - *Modeling methodology (e.g., linear programming, thermodynamic, etc.)*
  - *Model platform (e.g., GAMS, ASPEN, etc.)*
  - *Model limitations*

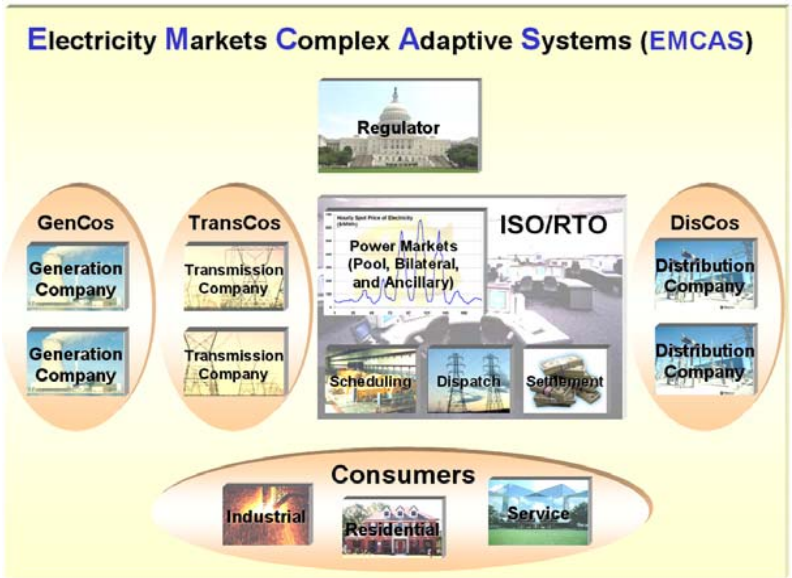
Gasoline Is Highly Dependent on Cost of Feedstock H_2 Cost Depends on Processing and Distribution

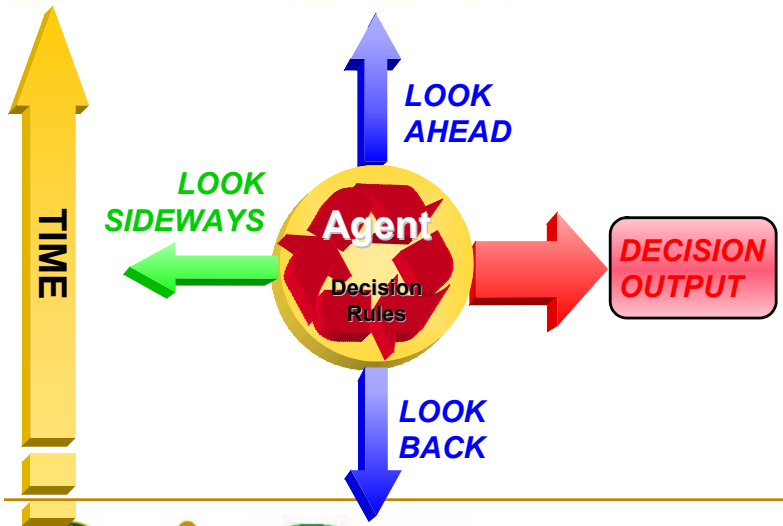


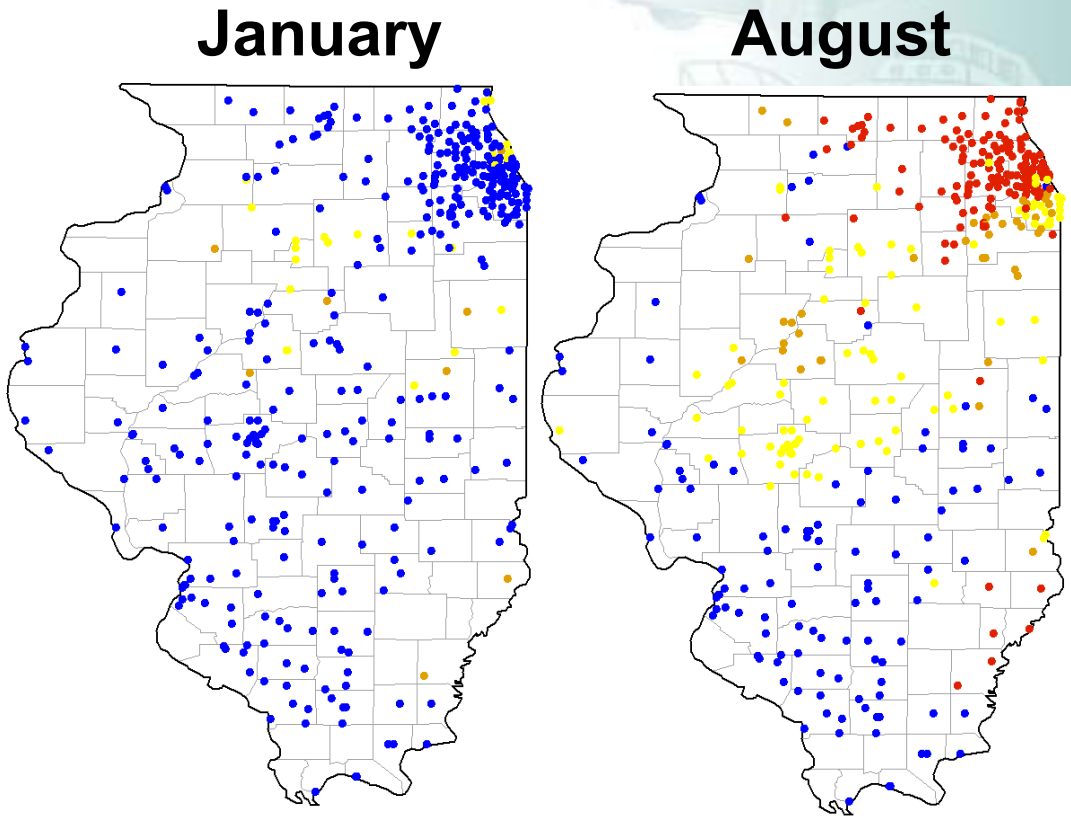


- Gasoline ~$1.00-1.25/gal untaxed ($28-40/bbl)
- H_2 >$2.50/gge at high volume, much more at low volume
- Feedstock >60% for gasoline vs. 25-35% for NG-based H_2, much less for coal or nuclear
- Distribution <10% for gasoline vs. 20-25% for centralized H_2
- Production ~20% for gasoline vs. >60% for H_2 from nuclear, ~25% from NG.
- Levelized costs decline as infrastructure is “built out”

An Agent-Based Complex Adaptive Systems Approach Simulates Electricity Markets in the Midwest







Transmission Constraints Contribute to Substantial Price Pressures in Summer

Argonne – the First National Laboratory (1946)

- ANL has been doing systems analysis since 1971
- The Center for Transportation Research has over 25 years of experience providing high-quality analysis
- Significant history of working in partnership with industry
- Analytical work has spanned the range of:
  - ✓ Energy Supply – globally and by region
  - ✓ Demand for transportation fuels – globally and region
  - ✓ Assessment of vehicle technologies and fuels
  - ✓ Economic analysis and interaction between energy prices and macroeconomic activity
  - ✓ Life-cycle analyses of energy use and environmental impacts associated with transportation technologies and fuels
  - ✓ Evaluate policies to accelerate transitions to new fuels and vehicles
- Hydrogen has been a part of our analyses since 1993

Change in Fleet Share Takes Longer Than for New Vehicle Technologies to Be Adopted